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Coherent Laser Radar Remote Sensing

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Thomas J. Alpert, Major, USAF
Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

COHERENT LASER RADAR REMOTE SENSING

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Group 53

FINAL REPORT TO THE
AIR FORCE ENGINEERING AND SERVICES CENTER
AND
AIR FORCE AEROSPACE MEDICAL DIVISION

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ABSTRACT

This report summarizes the technical effort accomplished in FY82 on a program to make range-resolved measurements of chemical agents or pollutants distributed within the atmosphere. The rationale for using compact, coherent CO_2 laser radar techniques (rather than TEA laser techniques) is discussed. Range-resolved measurements of aerosol backscatter at ranges up to 1.5km are reported. Techniques for making CO_2 lasers rapidly tunable among several wavelengths are also described.

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I. INTRODUCTION

This is the FY82 final report on the program entitled "Coherent Laser Radar Remote Sensing" supported by the Air Force Engineering and Services Center (AFESC) and the Air Force Aerospace Medical Division (AFAMD). The work reported here was initiated in April 1982 and will continue through FY83.

The specific tasks required under this program include 1) modification of the receiving electronics of an existing coherent, CO_2 laser radar to permit range-resolved measurements of aerosol backscatter at a single wavelength in several range bins simultaneously, 2) measurement of atmospheric aerosol backscattering cross-sections at a single wavelength, and 3) modification of the laser transmitter to allow operations at two wavelengths.

In this report in section II we present a general discussion of the rationale for using compact, coherent laser radar techniques for the detection of chemical agents or pollutants. Section III is a summary of the results of the measurements made to date. Two techniques for making CO_2 lasers rapidly tunable among several laser wavelengths are described in section IV. The Appendix contains a brief description of the Lincoln Laboratory transportable laser radar that has been used to make these measurements.

II. BACKGROUND AND THEORY

Lincoln Laboratory has begun a program to demonstrate the ability to detect low concentrations of chemical agents with a heterodyne laser radar. One potential approach is the use of differential absorption lidar (commonly referred to as DIAL). In this technique two laser pulses are transmitted: one whose frequency lies on a resonant absorption of the chemical agent and another whose frequency is off resonance. DIAL systems using CO_2 TEA laser transmitters and direct-detection receivers have yielded path-averaged concentrations for signal returns from retro-reflectors or topographic targets.[1] We have proposed to increase the effectiveness of the DIAL technique by using the naturally occurring aerosols as a distributed backscatterer. This task could be performed by a high power CO_2 TEA laser and a direct detection receiver; however, there are a number of advantages in using heterodyne detection. The low noise power associated with heterodyne detection reduces the required transmitter power so that a low pressure Q-switched CO_2 laser can be utilized. This type of laser can operate at much higher pulse repetition frequency (20-50kHz) than is available from CO_2 TEA lasers (1-100Hz). This means that the data collection time will be greatly reduced with the heterodyne detection system.

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Of fundamental importance in determining the utility of a tactical CO_2 radar as a DIAL sensor is the detectability of aerosol backscatter with such a system. The monostatic radar equation for the heterodyne-detected aerosol backscatter is

$$P_R = \frac{P_{AV}}{N_D \; PRF} \; \frac{\pi D^2}{8R^2} \; \epsilon \; \beta \; c \; e^{-2\alpha R}$$

where

P_R	=	average received power
P_{AV}	=	average laser power
D	=	transceiver optics diameter
c	=	speed of light
ϵ	=	optical/heterodyne efficiency
β	=	aerosol backscatter coefficient
α	=	attenuation coefficient (typically 1-3dB/km)
R	=	range
N_D	=	number of detectors
PRF	=	pulse repetition frequency.

With a sufficiently strong local oscillator laser, the average noise power in a heterodyne-detection receiver achieves the photon shot-noise limit

$$P_N = \frac{h\nu B}{\eta}$$

where

B	=	the intermediate-frequency (IF) bandwidth of the receiver ($\sim$ 1/pulse width = $1/\tau$)
ν	=	laser frequency
η	=	detector quantum efficiency

Table I gives the parameter values for the existing transportable CO_2 radar system used to obtain the data presented below. The average noise power in this system is of the order

$$P_N = 1.1 \times 10^{-13} \text{ W} .$$

At a range of 1km using the typical values $\beta \approx 10^{-7} \text{ m}^{-1} \text{ sr}^{-1}$ and $\alpha = 1.0\text{dB/km}$ this radar should collect an average backscatter power

$$P_R = 1.9 \times 10^{-12} \text{ W},$$

which implies a carrier-to-noise ratio

$$CNR = \frac{P_R}{P_N} = 17 .$$

By way of comparison, a direct-detection CO_2 radar with the parameters of Table I would collect the same P_R but with a P_N of 10^{-10} to 10^{-11} W. Thus, the heterodyne-detection radar has a 20-30 dB performance advantage over the direct-detection radar. This means heterodyne-detection systems can use transmitter powers (e.g., Table I) at which direct-detection systems are unusable.

To this point only average received backscatter power has been considered, i.e., the CNR is the ratio of the average received backscatter power to the average noise power for a single pulse. Because a coherent source is used as the transmitter, the backscatter power is a laser speckle phenomenon, which severely impacts measurement accuracy. Indeed when the CNR

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TABLE I

CO_2 LASER RADAR PARAMETERS

Laser Power (P_{av})	3W
Pulse Repetition Frequency (PRF)	20kHz
Pulse Duration (τ)	350ns
Transceiver Aperture (D)	13cm
Number of Detectors (N_D)	1
Quantum Efficienty (η)	0.5
Optical Efficiency (ϵ)	0.5

is very high, a series of single-pulse measurements will have exponentially distributed random power fluctuations (Rayleigh distributed amplitude fluctuations) with mean value P_R. Heterodyne detection of this speckle process yields a single-pulse signal-to-noise ratio

$$\text{SNR} = \frac{\text{CNR}/2}{1 + \text{CNR}/2 + (2\text{CNR})^{-1}} .$$

Note that for CNR >> 1 the effective SNR = 1. This is the well known unity signal-to-fluctuation ratio of laser speckle. The same upper limit on SNR applies to direct detection when using a diffraction-limited optical setup as would be employed for heterodyning. In either system, therefore, some technique is required to reduce the effects of speckle. The most viable speckle-reduction technique for heterodyne detection is multiple-pulse averaging. When N pulses are averaged together the measurement accuracy of the intensity return is

$$\delta = (N \cdot \text{SNR})^{-1/2}$$

where SNR is the single pulse result cited above. For high carrier-to-noise ratios (CNR > 10) SNR = 1 prevails and the measurement accuracy equals $N^{-1/2}$.

When measurements are made at low carrier-to-noise ratios (CNR << 1) SNR = $(\text{CNR})^2$ << 1 prevails so that many more pulses must be averaged to obtain any particular accuracy.

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III. EXPERIMENTAL RESULTS

Lincoln Laboratory is currently operating a heterodyne detection laser radar. It is a truck mounted system which provides both range and intensity imagery. This transportable system is described further in Appendix A and in reference 2. In order to detect aerosol backscatter the system was operated in its stare mode and a modification in the electronic processing was required. The existing electronics were designed for the detection of hard targets. A peak detection system is used to find and record the largest return within an adjustable range gate. By using narrow range gate settings the peak detection system was able to measure the returns from the atmospheric aerosols at the preset range. To detect returns at other ranges requires changing the location of the range gate manually. A more efficient method is to measure the backscatter from all ranges simultaneously on each pulse. A new electronics package to do just that is currently being assembled. It will process and record the information in real time at an effective rate of 8.3kHz. The data will be stored on digital tape for off line processing and analysis.

A number of samples of aerosol backscatter was collected on various days (see Table II) using the existing peak detection electronics. Such data did demonstrate that the aerosol returns were being observed. However data collection was very tedious.

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TABLE II

SUMMARY OF AEROSOL MEASUREMENTS

DATE	T (°C)	RH	CONDITIONS	COMMENTS
4/14/82	14	38	Sunny	
4/21/82	10	95	Light Rain	
4/27/82	17	78	Cloudy	
5/6/82	21	34	Overcast	
5/7/82	18	37	Clear	Nicolet
5/14/82	15	53	Cloudy	Nicolet, Gas Cell, Calibration plates
5/24/82	23	79	Foggy, Drizzle	Norfolk, VA Swirling Fog
8/24/82	24	60	Overcast	

Since the new electronics were not available we temporarily replaced the peak detection electronics with a commercially available digital oscilloscope. A block diagram of the system is shown in Figure 1. With this 20MHz digital oscilloscope the returns from 75 different ranges between 0.2km and 1.5km were measured and recorded simultaneously for each pulse. Although the laser was pulsed at 20kHz, the collection time for 2500 samples of data was approximately 3 minutes due to a memory dump-time limitation. Nevertheless, the 3 minute collection time was sufficiently short that the aerosol distribution remained essentially constant. The result of averaging these 2500 samples is shown in Figure 2 (data are shown as circles). The weather on that day was clear with high visibility. The estimated attenuation coefficient based on temperature and humidity was 1.2dB/km. The theoretical curve shown has a $1/R^2$ dependence which is modified by the atmospheric attenuation. The amplitude has been scaled to provide the best fit at a range of 0.5km.

The results show that aerosol backscatter can be observed with the existing transportable system out to a range of 1.5km. At ranges less then 0.5km the signals were lower than that predicted by theory. This effect is caused by operation in the near field of the transmit beam. The signal at short ranges could be optimized but this would require that the focus of the telescope

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RECEIVE BEAM

TRANSMIT BEAM

POINTER SCANNER

TELESCOPE

IMAGE PLANE SCANNER

PULSED TRANSMITTER LASER

LOCAL OSCILLATOR

HP 9845 B OFF-LINE PROCESSING

TRANSMIT RECEIVE SWITCH

20 MHz NICOLET DIGITAL OSCILLOSCOPE
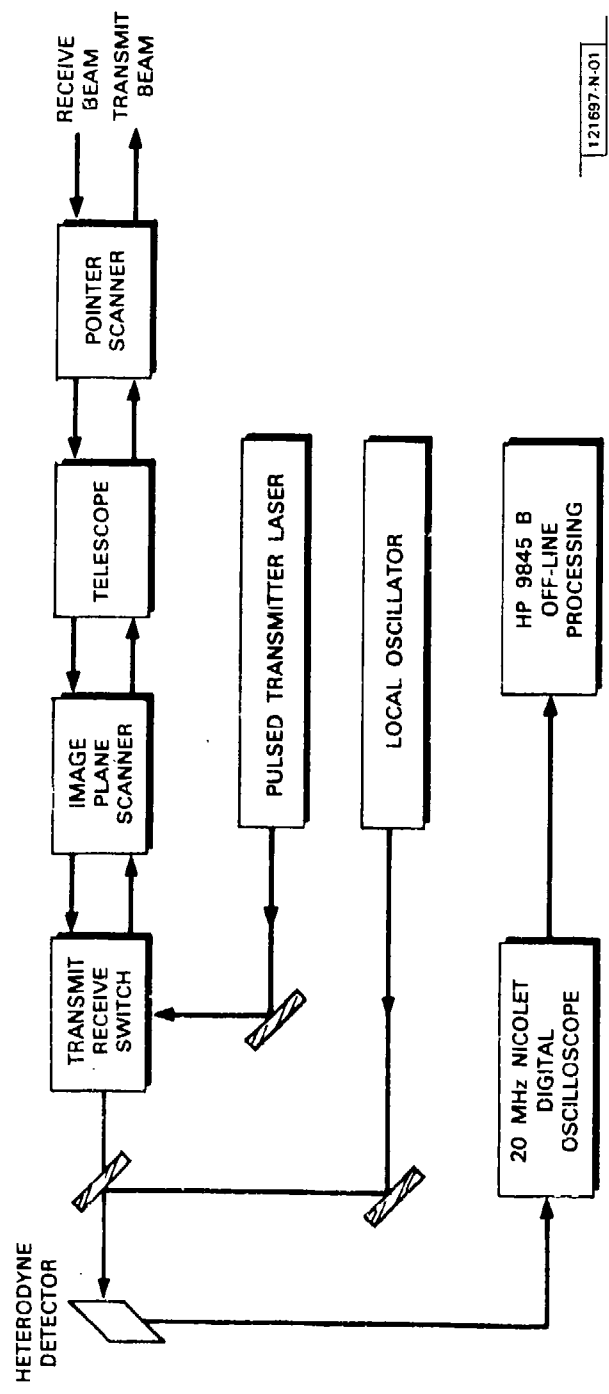
HETERODYNE DETECTOR

121697-N-01

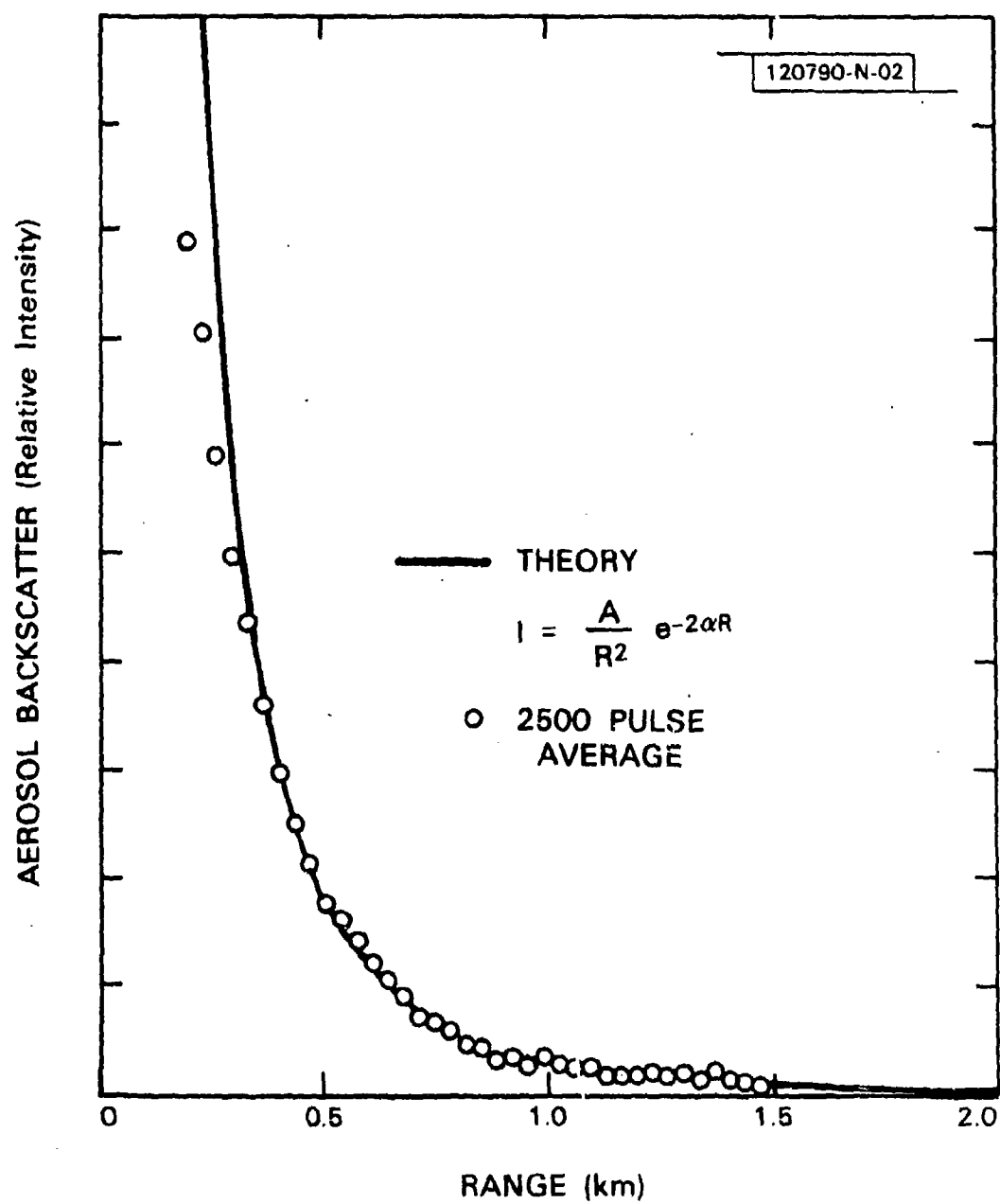Fig. 1.   Block diagram of the range-resolved aerosol measurements system.

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Fig. 2. Aerosol backscatter signal as a function of range. Each point represents the average of 2500 returns.

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be adjusted. To provide some absolute calibration of the amplitude, the signal returns were compared with those from an aluminum calibration plate at the same range. These measurements gave the volume backscatter coefficient $\beta = 2 \times 10^{-7} \text{ m}^{-1} \text{ sr}^{-1}$ in agreement with accepted values. A check was run on the correlation of the pulse to pulse return. The autocorrelation was found to be negligible on the inter-pulse time scale (50 μsec) and agrees with measurements made by others[3]. This implies that each pulse represents an entirely random sample, suitable for multiple-pulse averaging.

A check was made on the statistics of the return amplitudes from the aerosols. Shown in figure 3 is a histogram (2500 measurements) of return amplitudes from a fixed range (~ 0.5km). The plot shows the number of occurrences of a voltage level versus that voltage level. The return power is proportional to the voltage squared. For a pure speckle target the voltage should be Rayleigh distributed, i.e., the histogram should follow the probability density

$$\rho\,(V) \;=\; \frac{2V}{(V^2)_{avg.}} \quad\quad \exp\left[-\frac{V^2}{(V^2)_{avg.}}\right]$$

where $(V^2)_{avg.}$ is the average of the voltage squared. A Rayleigh curve which has been normalized to the total number of occurrences and the mean is also shown in figure 3. The Rayleigh amplitude
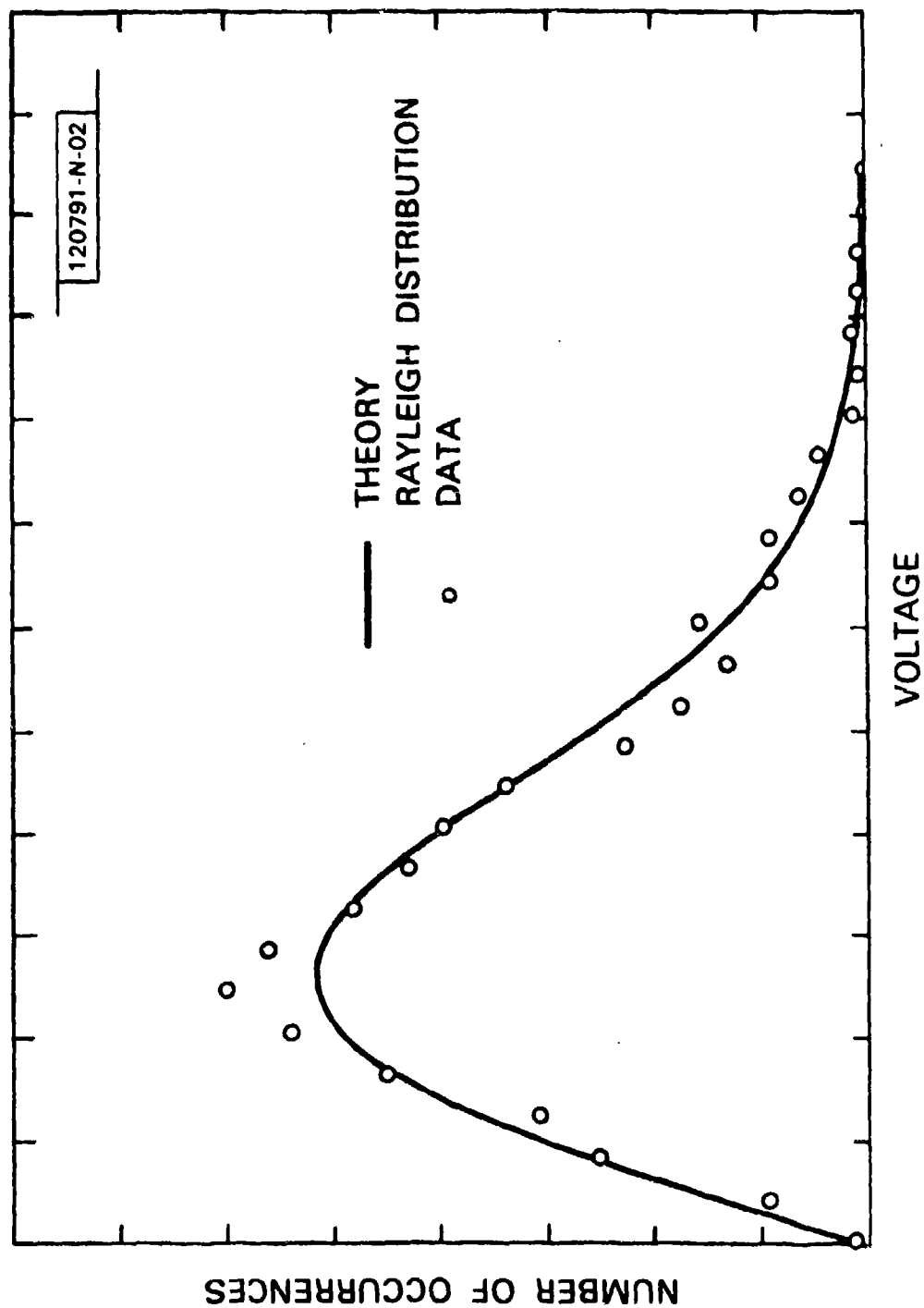
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Fig. 3. Histograms of 2500 aerosol backscatter measurements at a fixed range (∿ 0.5km).
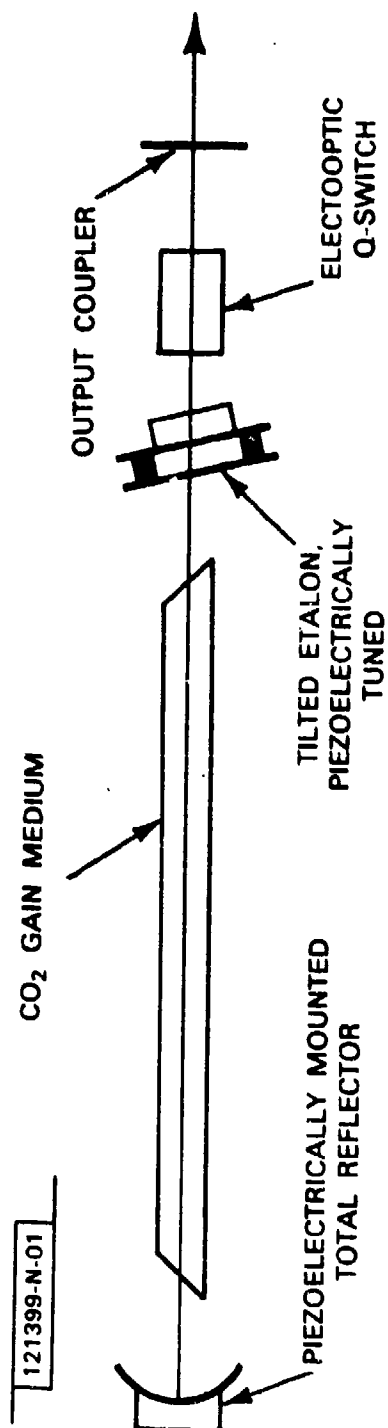
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distribution is equivalent to an exponential power distribution for which the mean equals the standard deviation. The data shown in figure 3 when squared and averaged did show a mean value approximately equal to the standard deviation. This confirms that the aerosol returns are indeed behaving as speckle targets.

IV. FREQUENCY AGILE CO_2 LASERS

For a chemical agent detection system, it will be necessary to utilize a frequency agile CO_2 laser source. Such a laser would ideally be able to randomly select any desired CO_2 emission line, and switch between lines in times less than a second. Two techniques are under consideration.

One technique for rapid tuning of the CO_2 laser wavelength is illustrated in figure 4. With this configuration, which employs an intracavity tunable etalon, the laser can, in priniciple, be tuned over all lines of the $9\mu m$ and $10\mu m$ bands. The etalon is tilted slightly in the cavity so that all radiation not at the resonant frequency is reflected off-axis, resulting in high cavity losses. By piezoelectric tuning of the etalon spacing, the resonant frequency, and hence the wavelength of the laser output, can be tuned over the desired interval. For each wavelength, the laser power must be maximized by tuning the overall cavity length.

The free spectral range of the etalon is $1/2t$ cm^{-1}, where t is the etalon spacing. Therefore, in order to tune over both bands

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CO$_2$ GAIN MEDIUM

OUTPUT COUPLER

ELECTOOPTIC Q-SWITCH

TILTED ETALON, PIEZOELECTRICALLY TUNED

PIEZOELECTRICALLY MOUNTED TOTAL REFLECTOR

TYPICAL ETALON CHARACTERISTICS

SUBSTRATE MATERIAL	ZINC SELENIDE
SPACING	25 μm
FREE SPECTRAL RANGE	200 cm^{-1} (Covers Both 9 μm and 10 μm Bands)
PEAK TRANSMISSION	95%

Fig. 4. Frequency agile electrooptically Q-switched CO$_2$ laser diagram.

($\approx 200\mathrm{cm}^{-1}$) a spacing of $25\,\mu\mathrm{m}$ is required. Another important etalon parameter is the resonant transmission. This must, of course, be maximized to minimize the insertion loss and concommittant laser power reduction. This parameter is highly sensitive to both mirror flatness and absorption losses. For example to obtain a 95% throughput with 80% reflecting mirrors, the absorption must be limited to .5% per surface, and the flatness to $\lambda/300$ or better[4]. The finesse of this etalon would be 14, insufficient to resolve adjacent laser lines. Rotational competition effects within the laser medium, however, would tend to favor one line over another, even for a very small differential net gain. Furthermore, the resolution of the etalon can be traded off against the tuning range by choice of spacing. The performance characteristics within a given laser must be determined experimentally. Another uncertainty which awaits experimental investigation is repeatability. That is, can one predictably access a given line with the application of a given voltage to the etalon?

We have fabricated such an etalon in the laboratory using available components and have achieved a transmission of 85%. Due to dimensional instabilities, we were unable to test it in a cavity. We currently have on order a commercial model with which we plan to test the feasibility of this concept.

In a second approach being pursued for this purpose it is proposed to use a tunable acousto-optic filter as an intracavity element to rapidly select a specific line for laser oscillation. Figure 5 illustrates the configuration of such a laser. The Bragg filter operates on the principle of acousto-optic light deflection. If light of the proper wavelength enters the filter at the Bragg angle σ, it will be deflected out at the same angle σ providing that the filter is being driven at the proper RF frequency. This mathematical relationship is shown in Figure 5. In the case of a laser, the angle σ for which gain is achieved is determined by the optical cavity. It can then be seen from the Bragg angle relationship that the product λF must be a constant for any given σ. Thus, as F, the RF drive frequency, is changed, the wavelength for which this cavity has gain must change. This allows the optical cavity to be tuned across a wide wavelength range by merely changing the RF drive frequency to the filter. Two passes are made through the filter (thus requiring the "bow tie" shape) in order to null out an undesired frequency shift imparted to the optical beam by the filter.

If this experimental laser configuration is successful, it would be superior to other tuning techniques in terms of thermal and vibration stability, tuning range, and ease of selection repeatability (due to RF frequency rather then DC level tuning).
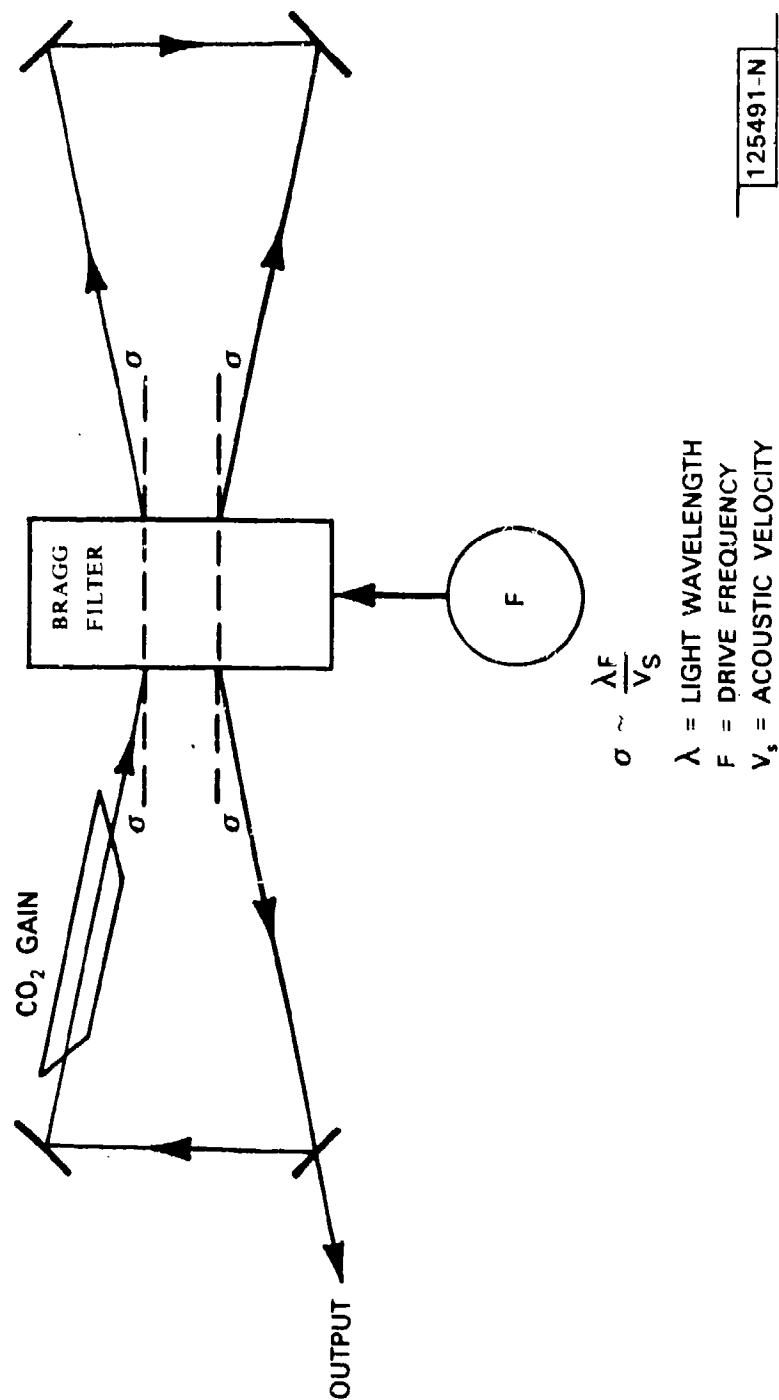
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$$\sigma \sim \frac{\lambda F}{V_S}$$

λ = LIGHT WAVELENGTH
F = DRIVE FREQUENCY
V_s = ACOUSTIC VELOCITY

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Fig. 5. Frequency agile acousto-optically driven CO_2 laser diagram.

At the present time, this is an entirely new and unproven technique for laser tuning. As such, it is considered a backup technique to the etalon tuning scheme discussed above.

V. SUMMARY AND CONCLUSIONS

We have demonstrated that a transportable, coherent, CO_2 laser radar has the ability to make range-resolved measurements of the backscatter from naturally occurring aerosols out to a range of 1.5km. The statistics of the backscatter return obey a Rayleigh probability distribution in amplitude which is theoretically expected. The signal returns have a decorrelation time less than the interpulse time of the radar so that many returns may be rapidly accumulated to provide the required measurement accuracy.

The system has not yet demonstrated a successful differential absorption measurement on any species. Initial experiments are planned to demonstrate absorption using a single laser wavelength by releasing an absorber into the beampath.

Work is in progress to construct a laser rapidly tunable over at least two wavelengths. This laser will then be used to demonstrate a two-wavelength DIAL measurement.

The progress made to date supports the conclusion that a reasonable compact, coherent laser radar may be used to search for, detect, and map absorbers in the atmosphere in a rapid manner.

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2. R. C. Harney and R. J. Hull, Proc. SPIE 227, 167 (1980).

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4. S. P. Davis, Appl. Optics 2, 727 (1963).

APPENDIX A

TRANSPORTABLE CO_2 LASER RADAR SYSTEM

SYSTEM DESCRIPTION

The transportable laser radar is an imaging coherent $10.6\mu m$ laser radar contained within a truck. The system's instantaneous field of view is $200\mu rad$. The transmitter is a nominal 10 watt CO_2 laser which can transmit beam shapes matched to the receiver field of view. The radar can operate at either a 15Hz frame rate or a 1Hz frame rate. The receiver consists of a 12 element array of detectors illuminated by a local oscillator. The detectors can all be illuminated simultaneously to image a 200 x $2400\mu rad$ spot. A scanner sweeps the illumination/receiver pattern over a 12 x 12mr FOV which is the final frame size.

By using the full 12 element detector array images can be produced at 15 frames/sec. This is useful for imaging dynamic targets. For signature measurements, only a single detector is used, and data is produced at one frame/sec.

In addition to the two frame rates the system may also be operated in a stare mode and a line scan mode. In the stare mode, the galvonometer scan mirrors are stopped so that a single field in space is sampled at the basic 18.9kHz pulse repetition frequency. In the line scan mode the elevation mirror is stopped so that a single line in azimuth is sampled 15 x 5 = 75 times/ second.

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The laser is operated in a Q-switched (pulsed) mode, with
one pulse illuminating each pixel of a frame of data. Range
information is obtained and recorded along with reflectivity
data. The intensity is recorded digitally to 8 bit accuracy, and
8 bits of range data are recorded with a range quantization of 6
meters. A boresighted visible TV camera is also used, and a
digitized frame of TV data is recorded. Figure Al is a line
drawing of the transportable system and Table Al specifies the
key parameters.

LOGISTIC SUPPORT

The system is accompanied by a towed 25kW, 3-phase generator
which provides all power requirements including air conditioning
for the truck. A supply of liquid nitrogen is required to cool
the detector arrays. Normally the only meteorological parameters
measured are the relative humidity, air temperature and an esti-
mated visual visibility. If other meteorological data is
required (turbulence level, etc.), it must be provided. RFI
problems appear minimal, although we have not yet worked in a
severe radar environment. The laser can be pumped and refilled
on site by a fill station located in the truck. Most components
have spares which are carried in the truck.

TABLE A1

TRANSPORTABLE INFRARED RADAR SYSTEM PARAMETERS

Laser Power (CW)	10 W
Pulse Repetition Frequency	18.9 kHz
Number of Detectors	12
Telescope Aperture	13 cm
Instantaneous Field-of-View	0.2 mrad
Imaging Field-of-View	12 mrad (Az) x 12 mrad (EL)
Estimated Maximum Range (3 dB/km Attenuation)	3 km
A/D Converter	8 bits Range/8 bits Intensity
Range Quantization	6.1 m or 20.0ft/Digital Count
Image Size	128 (horiz) x 60 (vert) Pixels
Real-Time Displays	
Boresighted LLLTV	Monochrome
Radar Image	Monochrome (Intensity or Range)
Digital Recording	
Radar Imagery	15 Frames/sec
TV Imagery	1 Frame/sec
Time, Temp, and Rel. Humidity	Once per Frame
Instant Tape Replay	

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SWING OUT DOORS

DIAGNOSTIC TEST EQUIPMENT

DUAL TV

KEYBOARD

PROTECTIVE OUTPUT WINDOW

APPROX. 16 × 8 ft FLOOR PLAN

8 × 2 ft OPTICAL BENCH RESTS ON FOUR SHOCK MOUNTS
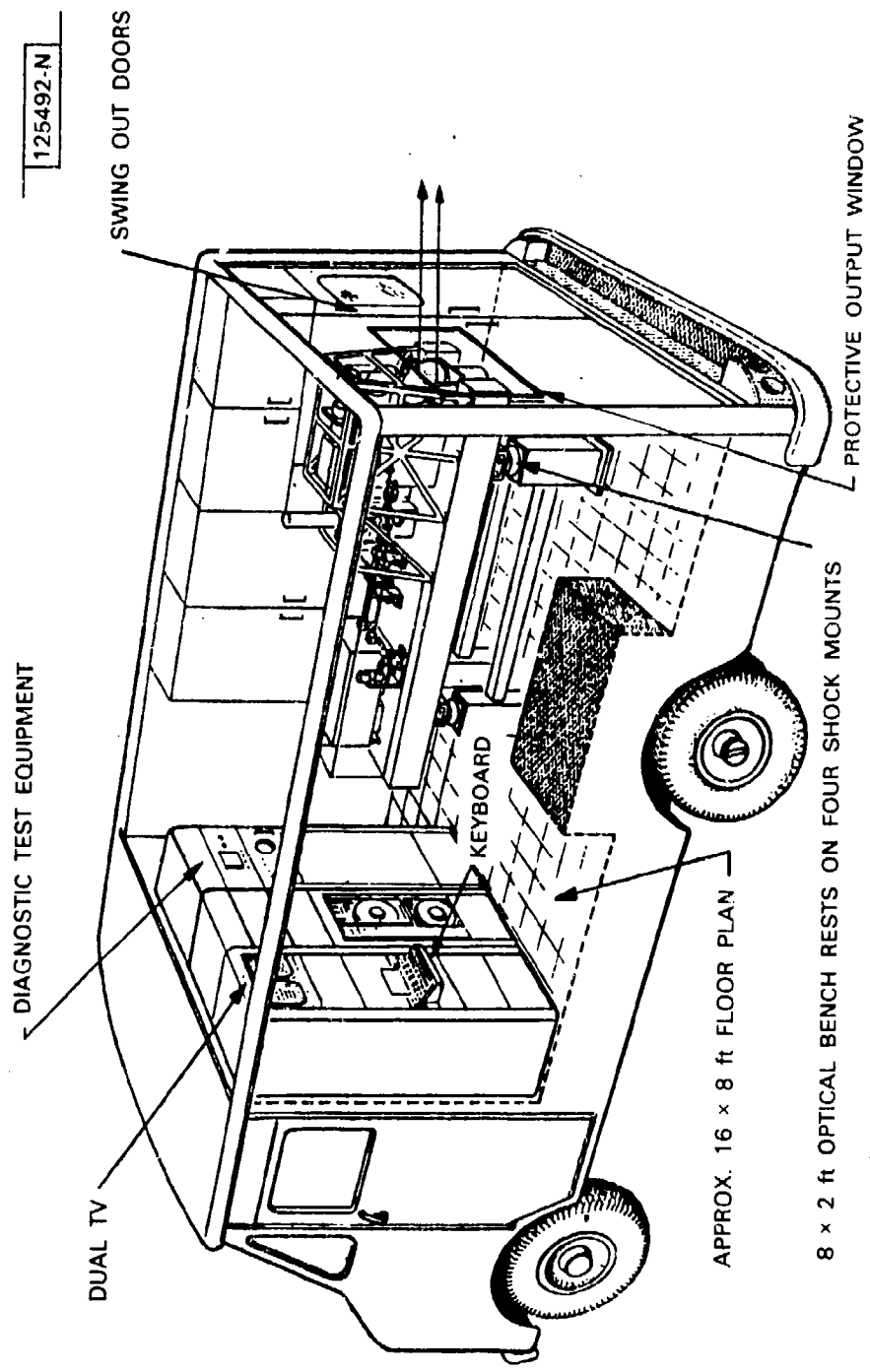
Fig. A1. Line drawing of the elements of the transportable laser radar system.

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This report summarizes the technical effort accomplished in FY82 on a program to make range-resolved measurements of chemical agents or pollutants distributed within the atmosphere. The rationale for using compact, coherent CO_2 laser radar techniques (rather than TEA laser techniques) is discussed. Range-resolved measurements of aerosol backscatter at ranges up to 1.5 km are reported. Techniques for making CO_2 lasers rapidly tunable among several wavelengths are also described.